Constraining Solar System impact history and evolution of the terrestrial planets with exploration of and samples from the Moon's South Pole-Aitken Basin

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Primary Authors
Brad Jolliff[1], Noah Petro[2]
[1]Department of Earth and Planetary Sciences, Washington University, St. Louis, MO 63130
[2]Planetary Geodynamics Lab, Code 698, NASA Goddard Space Flight Center, Greenbelt, MD 20771

Contributors and Co-signatories

Leon Alkalai, Jet Propulsion Laboratory
Carlton Allen, Johnson Space Center
Irene Antonenko, University of Western Ontario
Lars Borg, Lawrence Livermore National Lab
William Bottke, Southwest Research Institute
Barbara Cohen, Marshall Space Flight Center
Michael Duke, Retired, Co. School of Mines
Amy Fagan, Notre Dame University
Bernard Foing, European Space Agency
Lisa Gaddis, US Geological Survey
John Gruener, Johnson Space Center
Justin Hagerty, US Geological Survey
James Head III, Brown University
Harold Hiesinger, Westfälische Wilhelms-Universität Münster
Peter Isaacson, Brown University
Randy Korotev, Washington University
Georgiana Kramer, The Bear Fight Center
Samuel Lawrence, Arizona State University
Gary Lofgren, Johnson Space Center
Tomas Magna, Westfälische Wilhelms-Universität Münster
Clive Neal, Notre Dame University
Marc Norman, Australian National University
Larry Nyquist, Johnson Space Center
Gordon Osinski, University of Western Ontario
Dimitri Papanastassiou, Caltech/JPL
Carle Pieters, Brown University
Bhairavi Shankar, University of Western Ontario
Tim Swindle, University of Arizona
G. Jeffrey Taylor, University of Hawaii
Allan Treiman, Lunar & Planetary Institute
Paul Warren, UCLA
Mark Wieczorek, Institut de Physique du Globe de Paris
Ryan Zeigler, Washington University
Nicolle Zellner, Albion College

Summary

As the largest and oldest of the clearly recognizable impact basins on the Moon, the South Pole-Aitken (SPA) Basin holds many keys to understanding the impact history, formation of the crust, and global distribution of crustal materials. Because of its antiquity and stratigraphic position, SPA anchors the period of heavy impact bombardment that produced the scores of observable impact basins on the Moon. Dating impact-derived samples from SPA will allow determination of the chronology of the Basin and tests of orbital-dynamics models for impact bombardment of the inner Solar System during the first ~600 million years following accretion and early planetary differentiation. Because of its size, SPA likely excavated materials of the deep crust and possibly the upper mantle. Analysis of materials exposed at the surface of SPA will permit tests of models for the differentiation of the Moon. Understanding the age and characteristics of the impact that produced the Basin will allow a better understanding of the process of giant impact-basin formation and the role it played in modifying early planetary crusts. Sample return from the South Pole-Aitken Basin and investigation of the diversity and distribution of materials within the Basin will address issues of high scientific priority. These issues include understanding early Solar System history, planetary differentiation, and impact processes, with implications for the development of life and habitable environments on the early Earth.

The 2003 NRC Decadal Survey identified further exploration and sample return from the South Pole-Aitken Basin as among the highest priorities for Solar System science. The high priority of exploration of the SPA Basin for lunar and Solar System science was reaffirmed in 2007 by the NRC in two separate reports (2007a,b). For the same reasons now as then, collection of samples to date the SPA Basin's formation and test the impact cataclysm hypothesis and models for differentiation of the Moon remain high in priority.

Testing the Impact Cataclysm Hypothesis

One of the outstanding issues of planetary science is deciphering what happened in the Solar System, and the Earth-Moon system in particular, during the interval of ~ 3.8 to 4.0 billion years ago. According to the record derived from study of lunar samples collected by the Apollo Program, the Earth and Moon – and likely the rest of the inner Solar System – were bombarded by asteroid-sized objects, which formed giant impact basins found on all terrestrial bodies (e.g., Tera et al., 1974; Ryder, 1990). Similar impacts on Earth would have caused global changes in geology and climate that surely played a key role in the development and stability of habitable environments for the origin and early development of life (e.g., Schopf, 1999; Abramov and Mojzsis, 2009). Evidence from the lunar samples suggests that the heavy bombardment might have been confined to a relatively narrow interval of time, dubbed the lunar "cataclysm."

Whether the heavy bombardment was confined to such a narrow interval or simply represented the waning stages of prolonged planetary accretion is fundamentally important to understanding the evolution of the early Solar System. If such a bombardment occurred during a confined time interval, what caused it and what were the effects on early Earth? The ancient rocks needed to test the cataclysm hypothesis are extremely scarce on Earth because erosion and tectonic processes have erased most of the ancient rock record from those times. However, such rocks and ancient geologic terranes exist on the Moon and are accessible to test the hypothesis.

Other sample suites (e.g., HED meteorites, H chondrites, Bogard, 1995; Kring and Swindle, 2008) indicate that a similar bombardment occurred throughout the inner Solar System. Thus, the issue of the existence and magnitude of an impact cataclysm has a broad significance beyond lunar science; it is leading to a new paradigm for the dynamical evolution of the Solar System.

Attempts to explain a cataclysm as part of a declining flux of materials from accretion or Earth-Moon formation, or by breakup of main-belt asteroids, have been largely unsatisfactory (e.g., Morbidelli and Nesvorny, 1999; Hartmann et al., 2000; Bottke et al., 2007). Recent Solar System dynamical models, such as the “Nice model” (Gomes et al., 2005), involve an intense bombardment of the inner Solar System over a short period of time several hundred million years after planetary formation. According to the models, this bombardment was caused by migration of the orbits of the gas-giant planets. The Nice model also accounts for other Solar System features including the orbital inclinations and eccentricities of the gas giants and the existence of Jupiter’s Trojan asteroids (Tsiganis et al., 2005; Morbidelli et al., 2005). Ages of basin formation from SPA, including subsequent impacts within SPA Basin, will help discriminate among the various models. Untangling the bombardment history of the Moon is also described in detail in a white paper submitted to the NRC Planetary Science Decadal Survey, Inner Planets Panel, and titled “Lunar Bombardment History” by Bottke et al.

Because SPA is the oldest preserved lunar basin, its age is a crucial anchor point in the lunar impact-flux curve. If the SPA Basin formed close to 3.9 Ga, when the younger, near-side basins formed, then the cataclysm hypothesis would be strongly supported. If the age of formation of SPA is much older, then the cataclysm hypothesis would be weakened. However, success in testing the cataclysm does not rest solely on determining the age of SPA, itself. Superposed on SPA are many large impact craters, including several of basin size and the second youngest basin, Schrödinger (Fig. 1). Determining the system of ages or *chronology* recorded by rocks of SPA including those produced by smaller basins within SPA is of major importance to understanding the dynamical evolution of the Solar System and implications for evolution of the Earth and Moon.

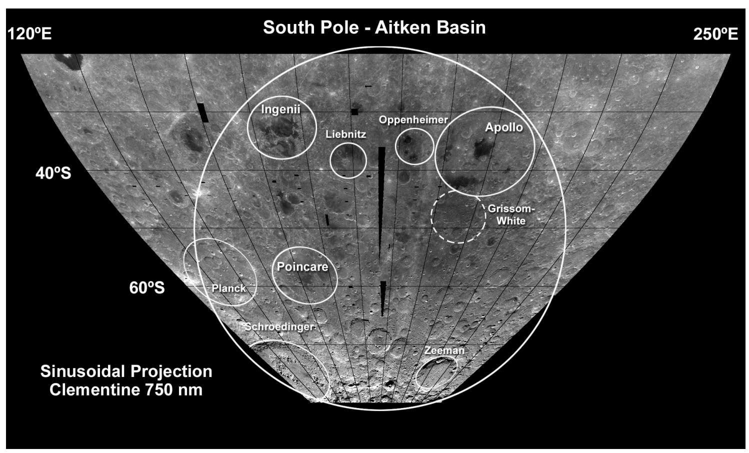

Figure 1. South Pole-Aitken Basin (approximated by large circle) showing locations of numerous smaller, superposed large craters and impact basins.

To determine the chronology of the SPA Basin, the age of rocks formed in the impact event(s) must be determined. Current understanding of impact-crater formation and products indicates that original (SPA) impact-melt rocks must be abundant throughout the interior of the SPA Basin. Crystalline impact-melt breccias were produced in all large lunar impacts and were found at all of the Apollo sites. Their relationship to a specific basin requires careful study, possible only through the combination of orbital mapping and petrologic, geochemical, and geochronologic studies of samples. Because of the number of large craters and basins that contributed ejecta to the SPA region, we expect there to be examples of impact-melt breccias from subsequent basins among the rocks of the basin interior. However, the SPA melt sheet, which is expected to have been 10s of km thick (Cintala and Grieve, 1998), forms the basin floor and will be the dominant material in the local regolith (Haskin et al., 2003; Petro and Pieters, 2004). Large impact craters that excavated through the megaregolith deposits have repeatedly excavated materials of the SPA Basin floor and distributed them across the Basin.

The SPA Basin is the best place to collect samples to test the cataclysm hypothesis in part because of its location on the lunar far side, far from the younger near-side basins in the regions explored by the Apollo and Luna sample-return missions. Impact-melt ages in the regions sampled by Apollo are dominated by the large, late basins, especially Imbrium (Haskin et al., 1998). Determining the age of the SPA Basin formation would provide a "book-end" for all of the stratigraphically younger impact basins on the Moon. Collection and return to Earth of the right samples from sites within SPA Basin would allow petrologic and geochemical analysis and radiometric age dating.

A large amount of impact melt was ejected from SPA during its formation. However, a larger volume of melt remained and solidified within the Basin interior. Thus samples of impact melt could be sought at or beyond the SPA Basin rim or in its interior. Owing to the many subsequent large impacts that struck the SPA region and redistributed materials, original SPA Basin deposits are increasingly diluted away from the Basin interior. The resulting unique geochemical signature associated with the SPA Basin interior is especially prominent in orbital data, particularly the gamma ray spectrometer data from Lunar Prospector (Fig. 2). Arguments based on models for the distribution of basin and crater ejecta, including the ballistic sedimentation of distal ejecta and consequent mixing of deposits indicate that in the interior of the basin, materials representing the original SPA-produced "substrate" still constitute a large proportion, i.e., 80%, or more of the surface deposits (Haskin et al., 2003, 2004; Petro and Pieters, 2004). Determining the chronology of cratering events within the SPA Basin will require a statistically significant number of samples of crystalline impact melt or impact-melt breccia (Cohen, 2009). Determining impact ages reliably requires multiple radiogenic dating techniques including K-Ar, Rb-Sr, Sm-Nd, and U-Pb. These methods have different susceptibilities to resetting by subsequent impact events; a consistent chronology must be sought from the full range of methods available. Trace siderophile-element analysis can be used to finger-print the impactor and test hypotheses for its origin (see Norman, 2009). The composition of the impactor and timing of the event provide critical constraints for Solar System evolution models because so little is known with certainty about the period of time between the formation of the Moon ~4.5 Ga and the formation of the Serenitatis/Imbrium basins ~3.9 Ga.

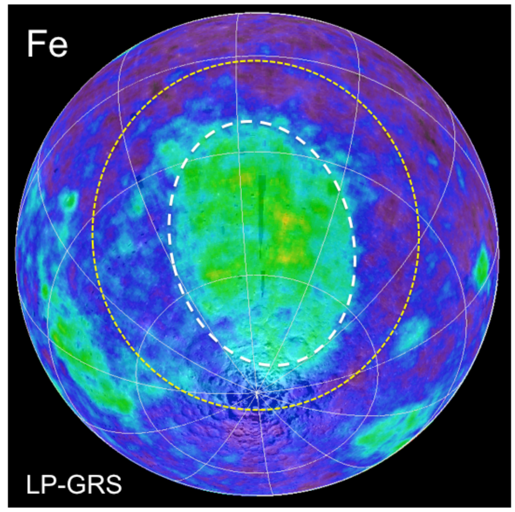

Figure 2. Map of Fe abundance within SPA basin (dotted line) showing areas of high Fe in green/yellow, low Fe in blue. Clear compositional differences between basin interior deposits and those of the surrounding lunar highlands are observed. Fe-rich materials from the original SPA Basin are present at the surface despite having been reworked by subsequent large impacts within the SPA Basin (Fig. 1).

There are different approaches to collecting the "right samples," but first, defining the "right samples" is key. Determining the age of the SPA Basin is of primary importance, but selecting an area that will allow determination of the ages of other large impact events (i.e., more recent basins or craters within SPA) will provide additional dates to anchor the chronology. One sampling strategy is to leverage the "natural" sampling mechanism afforded by random impact cratering, which delivers diverse rock samples to the lunar regolith where they can be accessed

from a surface lander at a single point. Another strategy is to use mobile sample analysis and collection to sample rocks within a region of interest. A third approach would be to include sampling as part of astronaut exploration. The first two approaches can be carried out robotically and for the cost approximately of a New Frontiers project.

Other science associated with exploration of the SPA Basin

The SPA Basin is a multifaceted exploration target in part because it contains abundant exposures of materials derived from the deep crust of the Moon and possibly the upper mantle, materials not found in abundance elsewhere on the Moon. The expansive and unique geochemical and mineralogical signatures associated with the Basin (Lucey et al., 1998; Jolliff et al., 2000; Pieters et al., 2001; Lawrence et al., 2002) indicate that the SPA interior preserves the original composition of source materials within the lower crust or upper mantle. Within the regolith are direct samples of materials excavated from great depth in the form of both clasts in breccia and impact-melt rocks, which are mixtures of the pre-existing target rock types. The large size of the Basin implies that impact melting extended into the upper mantle. Such mantle-derived impact-melt rocks would have a unique chemical composition relative to materials from the crust. Analysis of the deeply derived materials (mineralogy and geochemistry), coupled with ages and with geophysical and other remote sensing data obtained from orbit, will permit a better understanding – and modeling – of giant impact-basin formation processes and the effects of such events on early planetary crusts. Lastly, mare basalts also occur within the SPA Basin interior, although they are not as abundant as the voluminous near-side basin-filling mare basalts. Because of impact redistribution, fragments of these basalts are expected to be found mixed in the regolith at most locations within the SPA interior and will provide valuable information on the sub-SPA mantle.

Testing models for the differentiation and thermal evolution of the lunar crust and mantle and lunar bulk composition

Primary, deep-seated rocks from the lower crust of the Moon are rare in the Apollo and Luna samples, and have not, thus far, been found in lunar meteorites. The fact that the SPA Basin retains its mafic geochemical signature strongly suggests that deep crustal rocks are exposed and/or were incorporated into SPA impact melt and breccias that dominate the SPA regolith. One of the unsolved issues for the Moon and early crustal petrogenesis is the extent to which the crust is chemically and lithologically zoned with depth; did the primordial lunar crust form with a subsurface layer of anorthosite, zoning to progressively more mafic rock types such as norite, troctolite, or gabbro? If so, are the mafic components complementary to the ferroan anorthosites, crystallized from the magma ocean residual melt, or are they magnesian and associated with mantle melts that intruded the anorthositic crust? The answers to these questions bear on the thermal and magmatic evolution of the lunar interior as it transitioned from the magma-ocean stage. Orbital geochemical data are insufficient to answer this question, and surface materials are too complexly mixed to untangle the components with in-situ measurements; samples with geologic context from SPA must be analyzed in labs on Earth.

The SPA Basin is located on the opposite side of the Moon from the near-side regions that were well sampled by Apollo and Luna missions, and far distant from the effects of the large, late impact basins, especially Imbrium. Materials of the SPA basin thus present the opportunity to obtain and examine materials that are least affected by those events. Although there may be deposits in SPA antipodal to Imbrium and Serenitatis, the Basin is large enough that exploration and sampling can be done well away from those deposits. SPA materials will provide a crucial test of lateral heterogeneity as well as variations associated with depth in the crust. Understand-

ing the characteristics of the strong compositional asymmetry of the Moon that are indicated by orbital data remains a key element of testing models for the early differentiation of the Moon.

Among elements detected well from orbit is thorium, which is naturally radioactive. Thorium, along with U and to a lesser extent K, produces heat in the Moon's interior and plays a fundamental role in its magmatic and thermal evolution. On the Moon, Th is strongly concentrated in the crust, especially in the "Procellarum KREEP Terrane" (Jolliff et al., 2001), so much so that reasonable mass-balance models can be constructed and bulk compositions compared with bulk Earth or the terrestrial mantle. A key unknown in such models is the Th content of the lower crust. Materials formed at depth and now exposed within the SPA basin will provide improved knowledge of the distribution of radiogenic elements on the Moon, which will in turn provide strong constraints on the bulk-Moon composition and hypotheses for the origin of the Moon. Rock samples from well-selected sample sites are needed for trace-element analysis to understand the lithologic distribution of Th and related elements, and to "deconvolve" the orbital data.

Better understanding the giant impact-basin formation process

Knowledge of the composition, mineralogy, and ages of rock types of the SPA Basin is crucial to understanding how the Moon's crust responded to the impact. Understanding lithology, i.e., whether rocks are impact-melt or its crystalline derivatives, fragmental material, or crystalline bedrock – and in what proportions – and linking this information to remote-sensing data are needed to understand how materials were distributed by the impact. Progress in this area requires an integration of remote-sensing data, including spectroscopy (mineralogy and chemical composition) and geophysics (gravity and topography), with photogeologic and ground-based investigations, and analysis of samples from key locations. The first three of these topics can be done using existing spacecraft data, funded through R&A programs. Ultimately, samples from well-selected locations are necessary to interpret remote-sensing data in terms of physical and chemical properties of real rock components, including mineral/chemical indicators of depths of origin.

Sampling the far-side mantle beneath the SPA Basin

The unique geochemical signature associated with the interior of SPA is due to the enormous size of the basin and the depth of origin of material that is exposed at the surface. Mare volcanism has not filled a significant portion of the basin (Fig. 1), leaving the original interior exposed. However, the volcanic materials within SPA represent partial melts derived from the mantle below SPA, a thus-far unsampled source region of lunar volcanic materials. Obtaining samples derived from this portion of the lunar mantle would offer insights into the *global* heterogeneity of the mantle. The volcanic deposits provide valuable insights into the thermal and chemical evolution of the Moon, and they provide a critical link between mantle processes and their expressions on the surface of the Moon (e.g., Hagerty et al., 2006).

The abundance and variety of mare basalt and other volcanic deposits (e.g., pyroclastics, domes) on the Moon's near side are in contrast to the paucity of basalt and more restricted chemical and temporal variety on the far side. Ancient basalts that have been covered by younger light-colored impact deposits (cryptomare) are recognized, along with scattered, younger deposits, in SPA. Determining the age and composition of these basalts will greatly expand understanding of the lunar volcanic suite and why basalts are distributed so heterogeneously on a global scale. Investigation of SPA volcanic materials will test the hypothesis that a globally heterogeneous distribution of radiogenic heat-producing elements following the initial differentiation is related to the production and extent – spatially, chemically, and temporally – of far-side volcanism. Small samples of basalt and volcanic glass contained in regolith are adequate for the required chemical and isotopic analyses.

In addition to sampling volcanic materials, direct samples from the mantle may be accessible in locations where post-SPA craters have excavated to the mantle. Recent crustal thickness models based on data from the Kaguya mission suggest that the crust may be less than 10 km thick beneath the Apollo Basin and generally only 20 km thick elsewhere in SPA (Ishihara et al., 2009). Such thin crust implies that smaller craters within Apollo (e.g., Dryden) or larger craters across SPA (e.g., Poincaré, Fig. 1) may have exposed or excavated mantle materials.

Scale of Missions Needed and Relationship to other Missions

Two areas of lunar science have recently experienced significant activity leading to major advances. One is global remote sensing, from Galileo, Clementine, and Lunar Prospector in the 1990s to SMART-1, Kaguya, Chang'e-1, Chandrayaan-1, and LRO in this decade. The other is in the area of lunar meteorites, which are being discovered on Earth at a rapid pace and can be tied to broad regions of the Moon through global remote sensing data, thus expanding sample-based knowledge beyond the Apollo and Luna regions to a global perspective (e.g., Korotev et al., 2003). Although meteorites may be found or may exist that match aspects of the orbital geochemistry for SPA, samples with more certain geologic context are needed for ground truth.

Key approaches to achieve a quantum gain in our understanding of the Moon also must include geophysics to determine interior structure, field investigations (robotic or human) of geologic features that were not encountered at previous sites of surface exploration, and sample return from key locations. A separate white paper (Treiman et al.) discusses science that can be addressed broadly with new lunar samples of known geologic setting. Here, we focus on SPA, because samples from this part of the Moon offer the possibility to address key questions relevant to Solar System processes (orbital dynamics and critical events in the early Solar System). These investigations address the impact cataclysm, which would have been fundamentally important to the early history of Earth and development of life, as well as planetary-scale issues for the origin and evolution of the Moon (Kring, 2008). Exploration of the SPA Basin through direct collection and analysis of representative materials addresses issues as fundamental as the characteristics of the chemical reservoir from which the Moon originated, early differentiation and production of crust and development of global asymmetry, the relationship between magmatic activity and internal thermal evolution, and the effects of giant impact events on the terrestrial planets.

Landing on the Moon, collecting a set of samples, and returning them to Earth requires a New Frontiers-class mission, which has been demonstrated through the 2003 Planetary Science Decadal Survey and the New Frontiers proposal process.

Required Supporting Research and Facilities

A mission to collect samples from SPA Basin and return them to Earth is technically straightforward; robotic sample-return from the Moon was accomplished by the Soviets over 30 years ago (Luna 16, 20, 24). However, sampling the far side of the Moon poses a new set of challenges not faced previously. Technical advances in *in-situ* instrumentation are insufficient for the required isotopic, geochemical, and mineral-chemical analyses on the Moon; however, terrestrial laboratories and instrumentation can do the requisite analyses, even on very small samples. Nonetheless, expertise in the analysis of lunar samples and capabilities to work with small samples, must be sustained through core NASA R&A programs. Detailed mapping and scientific analysis need to (and now can) be performed, using available orbital spacecraft data, to identify the most valuable sampling locations. The intrinsic value of sample return from SPA is extremely high, not only for lunar science, but for Solar System science, including understanding the environment of early Earth.

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